

Patent Application

for

**A Method and System For Providing A Semi-Data Aided
Frequency Estimator For OQPSK**

by

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Field of the Invention

[0001] The present invention relates to a method and system for training a receiver, and more specifically, to a method and system for performing synchronization as part of the processing of a received signal in a radio communication system.

Background of the Invention

[0002] Radio communication systems involve the transmission of information over an air interface, for example, by modulating a carrier frequency with the transmitted information. Upon reception, a receiver attempts to accurately extract the information from the received signal by performing an appropriate demodulation technique. However, in order to demodulate a received signal, it is first necessary to synchronize timing between the transmitter and receiver. For example,

clocking differences between the transmitter and the receiver provide for differences in bit timing.

[0003] Moreover, in some radio communication systems, information is transmitted in bursts, sometimes referred to as "frames". In these types of systems, it is also desirable to locate the beginning of a frame, so that information relevant to a particular receiver is isolated and demodulated.

[0004] Unfortunately, there exists many challenges associated with synchronizing to a received signal. For example, although the receiver may be tuned to an assigned frequency on which its intended signal has been transmitted, Doppler shifting may result in a large frequency offset between the frequency to which the receiver is tuned and the actual frequency of the desired information signal when it reaches the receiver after having traveled through the air interface. Moreover, the crystal oscillator used in the receiver is only accurate to within a certain number of parts per million, which may introduce an additional frequency offset.

[0005] In addition to an unknown frequency offset, a receiver must also cope with unknown phase accuracy, i.e., the receiver does not know the difference between the phase of the signal generated by its synthesizer at power-on and the phase of the received signal. Thus, the receiver faces at least three challenges in synchronizing to the received signal: unknown timing, unknown frequency offset and unknown phase. For timing and phase offsets relatively short training sequences can provide satisfactory estimation results. However, short training sequences do not provide satisfactory frequency estimation using current methods.

[0006] One method of over coming these challenges, the data aided technique, uses a long training sequence to estimate the frequency

parameters. This requires significant overhead and time to train the receiver. For example, burst modems require around 100 symbols to get an accuracy of 10^{-4} relative to symbol rate at a signal to noise ratio of $E_s/N_0=5\text{dB}$. Since burst lengths can be as short as 200 symbols, large overheads can be prohibitive and result in reduced throughput.

[0007] FIG. 1 is a graph 100 depicting the data-aided Cramer-Rao Bounds for frequency estimation. Specifically, graph 100 shows the theoretical bounds for a modem training sequence where a separate training sequence is communicated with the data. The training sequence is used to synchronize the signal and the data is then capable of being processed by the receiver. The horizontal axis depicts how many symbols are required to be communicated in order to train the receiver while the vertical axis depicts the accuracy of the estimation. As discussed above, the data aided approach reduces throughput because of the training sequence that must be sent. For example, Internet data can be as short as 200 symbols while the training sequence required would be 100 symbols, which is not efficient because half of the bandwidth is dedicated to the training sequence.

[0008] Specifically, FIG. 1 plots the following modified Cramer-Rao bound for frequency estimation which can be represented by the following equation:

$$\sigma^2(f) \geq \frac{3}{2T^2\pi^2N^3} \cdot \frac{1}{E_s/N_0}, \quad (1)$$

where T is the symbol duration and N is the length of training sequence. The modified Cramer-Rao bound is a lower bound for an unbiased estimator. The bound can be re-arranged as

$$2\pi\sigma(f) \geq \sqrt{\frac{6}{N^3 E_s / N_0}}. \quad (2)$$

As can be seen from the FIG. 1, in order to achieve 10^{-4} accuracy, the training sequence has to be at least 175 symbols at 5 dB E_s/N_0 .

[0009] FIG. 2 is a graph 200 depicting a non-data aided Cramer-Rao bound for frequency offset. Compared to graph 100, graph 200 shows that training takes much longer to achieve the same accuracies compared to graph 100. The non-data aided approach takes much longer to train a modem. However, the benefit is that the training sequence is not required to be sent since synchronization is done before the data is received. Unfortunately, the time frame for synchronization using the non-data aided approach is prohibitive.

[0010] Without knowing the data, as expected, for estimation in the non-data aided case, performance is always poorer than in the data-aided case. Furthermore, non-data aided frequency estimation can be classified into timing aided or non-timing aided. Non-timing aided estimation typically has very poor performance. On the other hand, performance of timing aided estimation deteriorates very quickly if timing estimation becomes less accurate.

[0011] Current methodologies such as the data aided and non-data aided approach do not adequately eliminate and/or reduce these challenges to achieve sufficiently accurate synchronization at a high enough first frame success rate in the face of low signal-to-noise ratios. Therefore, it would be advantageous to provide new techniques for synchronizing to a received information signal that overcomes these drawbacks.

Summary of the Invention

[0012] The present invention relates to synchronization of digital radio signals using a semi-data aided algorithm for frequency estimation. The frequency estimator utilizes the phase and timing information to proceed to derive the frequency estimation based on the unknown information-carrying data. A mitigation strategy is applied to effectively combat timing imperfections in the frequency estimation.

[0013] Specifically, a system and method for synchronizing a communication signal is provided, comprising a satellite adapted to transmit a signal. The signal includes data information and synchronization information. A receiver adapted to process the signal received from the satellite and determine offset information from said received signal is also provided. The receiver includes at least a phase estimator adapted to estimate a phase offset of the received signal, a timing estimator adapted to estimate a timing offset of the received signal, and/or a frequency estimator adapted to derive a frequency offset from the phase and timing offset information from said received signal. The receiver further includes at least a phase estimator adapted to estimate a phase offset of the received signal, a timing estimator adapted to estimate a timing offset of the received signal, and/or a frequency estimator adapted to derive a frequency offset from the phase and timing offset comprising removing the modulation from the received signal. The received signal is sampled for information carrying data. A determination is made as to whether the step of sampling was done at a peak wave point of the data, and the step of sampling is repeated in a response to a determination that the sampling was not done at a peak wave point of the data.

Brief Description of the Drawings

[0014] The details of the present invention can be readily understood by considering the following detailed description in conjunction with an accompanying drawing, in which:

[0015] FIG. 1 depicts a graphical representation of a conventional data aided Cramer-Rao Bound illustrating an incident of frequency offset;

[0016] FIG. 2 depicts a graphical representation of a conventional non-data aided Cramer-Rao Bound illustrating an incident of frequency offset;

[0017] FIG. 3 depicts a high level communication system according to an embodiment of the present invention;

[0018] FIG. 4 depicts a graphical representation of frequency versus timing error according to an embodiment of the invention;

[0019] FIG. 5 depicts a graphical comparison of the root mean square errors of a modified CRB versus a basic algorithm according to an embodiment of the present invention;

[0020] FIG. 6 depicts a frequency histogram illustrating frequency offset according to an embodiment of the present invention;

[0021] FIG. 7 depicts a graphical representation of the probability distribution of various estimators having a signal to noise ratio of $E_s/N_0 = 5$ dB resulting from operation of a system and method according to an embodiment of the present invention;

[0022] FIG. 8 depict a graphical representation of a comparison of the RMS of various estimators resulting from operation of a system and method according to an embodiment of the present invention;

[0023] FIG. 9 depicts a graphical representation of a comparison of the RMS of various estimators having a signal to noise ratio of E_s/N_0

= 5 dB resulting from operation of a system and method according to an embodiment of the present invention;

[0024] FIG. 10 depicts a graphical representation of the probability distribution of various estimators having a signal to noise ratio of $E_s/N_o = 4$ dB resulting from operation of a system and method according to an embodiment of the present invention; and

[0025] FIG. 11 depicts a graphical representation of the probability distribution of various estimators having a signal to noise ratio of $E_s/N_o = 3$ dB resulting from operation of a system and method according to an embodiment of the present invention;

[0026] To facilitate understanding, identical reference numerals have used, where possible, to designate identical elements that are common to the figures.

Detailed Description of the Invention

[0027] FIG. 3 depicts a high-level communication system according to an embodiment of the present invention. Specifically, communication system 300 comprises a satellite 310 for transmitting receiving or relaying a communication signal 314 including a unique word for synchronizing a receiver 312. The receiver 312 includes a controller 312A for operating the receiver 312, a frequency estimator 316, a phase estimator 318 and a timing estimator 320.

[0028] It will be appreciated by those skilled in the art that the communication signal 314 can be a Time Division Multiple Access (TDMA) signal, Code Division Multiple Access (CDMA) signal, cellular signal or the like.

[0029] In communication system 300, satellite 310 transmits communication signal 314 to receiver 312. Offset Quaternary Phase Shift Keying (OQPSK) modulation can be used due to its near constant

envelope property. OQPSK is often used for a power limited system that needs to drive an amplifier close to saturation. However, other modulation techniques can be substituted and still fall within the scope of the present invention.

[0030] Communication signal 314 can be represented by the following equation:

$$s(t) = e^{j(2\pi f_f t + \theta)} \left\{ \sum_i a_i h(t - iT - \tau) + j \sum_i b_i h(t - iT - T/2 - \tau) \right\} \quad (3)$$

where $a_i, b_i \in \{1, -1\}$ represent data, $h(\cdot)$ is the shaping filter which is typically used when a signal is transmitted and the sender wants it to satisfy certain spectral requirements; and f, θ, τ are respectively a frequency offset, a phase offset and a timing offset. For coherent demodulation, the receiver 312 can estimate the unknown parameters f, θ, τ .

[0031] It will be noted that for each transmission burst, there is a short training sequence which comprises a unique word attached to the transmitted data of length M . The short training sequence comprises for instance, between about ten to twenty symbols. However, those skilled in the art will appreciate that the present range of ten to twenty symbols can vary and still fall within the scope of the invention. The unique word is a known sequence of symbols used by the receiver 212 for synchronization purposes. The receiver 212 utilizes this Unique Word to first obtain estimation for θ, τ as vectors $\hat{\theta}$ and $\hat{\tau}$.

[0032] For the non-data aided training algorithm, the first step is to remove the modulation from the received signal $x(t)$ where $x(t) = s(t) +$

noise. By squaring the incoming signal to obtain $x^2(t)$, though the modulation cannot be removed, the squared signal can be written as

$$x^2(t) = \alpha(e(t))e^{j4\pi f} + g(t), \quad (4)$$

where $e(t)$ is the error of time estimation. In other words, $e(t)$ is the time difference between t and the closet in-phase eye opening (also known as the point where the signal or amplitude is at its strongest), $\alpha(\cdot)$ is a periodic function of period T , the symbol duration of the incoming OQPSK signal, and $g(t)$ does not have any dominated signal at any single frequency, in other words, $g(t)$ is close to white noise (typically not Gaussian). $\alpha(t)$ is also the amplitude of the signal. Specifically, the accuracy of $\alpha(t)$ depends on knowing the time.

[0033] FIG. 4 illustrates $\alpha(t)$ with t being the time offset from the eye-opening of the in-phase signal. It is periodic with period T and $\alpha(t)$ degenerates to zero when it is off by $1/4$ of the symbol duration at $1/2$ a symbol, it is of the same magnitude at $t = 0$ with an opposite sign. The following frequency estimators are formulated based on these analysis.

[0034] Assume the peak of the signal is $u(n)$ which is represented by the equation

$$u(n) = x_I(n * T / 2 + \hat{t}) + jx_Q(n * T / 2 + \hat{t}) \quad (5)$$

with \hat{t} being the time offset estimated from unique word. Note that before symbol timing offset T is determined, the sampling typically will

not appear exactly at $n^*T/2 + \hat{\tau}$. In this case, interpolation can be used to obtain $u(n)$ from the original samples. It can be assumed that $u(0)$ corresponds to the estimated eye opening of the in-phase of the first symbol of the unique word, N is the length of the unique word and M is the length of the estimation window. The following equation computes the average

$$(x_1, f_1) = \max_f \left\{ \operatorname{Re} \left\{ \sum_{k=0}^{M-1} (u(2k)^2 - u(2k+1)^2) e^{-j(4\pi f k + 2\delta - 2\pi N f)} \right\} \right\}; \quad (6)$$

where χ_1 is the maximum values and f_1 are the frequencies to achieve the maximum value.

[0035] Assume that a unique word of length 24 and second order Lagrange curve fitting timing estimator. Also included are the nonlinear effect of the power amplifier. FIG. 5 depicts the root-mean-square of an estimator with 230 symbols. From the graph 500, it is clear that the estimation given by equation 2 as shown by plot 502 is about 1.5 dB away from the theoretical Cramer-Rao bound of plot 504. Note that the Cramer-Rao bound decays with the length of information-bearing sequence at the power of three and linearly decays in respect to the signal to noise ration (dB). This means that the 1.5 dB difference does not give a very big root mean square error degradation. In graph 500 the vertical axis depicts the signal to noise ratio, and the horizontal axis depicts the residual error.

[0036] Referring to FIG. 6, which is a histogram of FIG. 5, graph 600. Besides the root mean square error, it is also interesting to look at the histogram of the residual at the output of the frequency

estimator. The desired density of the residual frequency error is a Gaussian distribution which indicates that there is no dominated factor for the residual error frequency. Specifically, FIG. 6 depicts the histograms of the residual frequency at 5 dB Es/N0 with an estimation window equal to 230 symbols. The Gaussian distribution with the same standard deviation is also plotted. In the simulation, 128,000 symbols per second is assumed. From the plot 602, it is clear that for a small frequency (within 50 Hertz), the residual frequency error is approximated by the Gaussian distribution. However, for coded system, what is more relevant is large frequency errors that cause more damage while smaller frequency offsets can be tracked by a carrier recovery loop. However in plot 602, the density function at high frequencies is too small to be observed.

[0037] Referring now to FIG. 7 which depicts the cumulative probability for the same simulation of FIGs. 4-6, it is clear that the basic algorithm deviates from the Gaussian distribution quite significantly for large frequency errors. Rather than looking at the probability of error at 10 Hz, Fig. 7 shows cumulative error. For example, graph 700 shows the probability of error greater than 10 Hz which is more beneficial.

[0038] Re-examining FIG. 4, it can be observed that for any given timing error residual $e(t)$, if $a(e(t))$ is small, $a(e(t) + T/4)$ will always have reasonable high magnitude. This motivates the following modification of the basic equation 6 which depends less on the initial timing estimation. If the initial timing estimation was wrong another estimation is required.

[0039] In addition to the equation 6, further computations lead to the following equation

$$(x_2, f_2) = \max_f \left\{ \left| \operatorname{Re} \left\{ \sum_{k=0}^{M-1} (v(2k)^2 - v(2k+1)^2) e^{-j(4\pi \hat{T} k + 2\hat{\theta} - 2\pi N \hat{f})} \right\} \right| \right\}, \quad (7)$$

where $v(n) = x_1(n * T/2 + \hat{T} + T/4) + jx_2(n * T/2 + \hat{T} + T/4)$. The final estimated frequency is taken as f_1 if $x_1 \geq x_2$, otherwise, it is taken as f_2 . Note that equation (7) is different from equation (6) not only with respect to having different inputs $u(\cdot)$ versus $v(\cdot)$, but also equation (7) takes the maximum over the absolute value. This is due to the fact that it cannot be known whether the timing estimator advances or lags the true timing offset. For example, the first estimate may have been a $1/4$ symbol off, but it is not known whether there was a lag or lead. Taking the absolute value accounts for the lag or lead.

[0040] In the case that $u(0)$ corresponds to the end of the unique word, equation (6) and (7) should be replaced respectively with

$$(x_1, f_1) = \max_f \left\{ \left| \operatorname{Re} \left\{ \sum_{k=0}^{M-1} (u(2k)^2 - u(2k+1)^2) e^{-j(4\pi f k + 2\hat{\theta} - 2\pi N f)} \right\} \right| \right\}, \quad (8)$$

$$(x_2, f_2) = \max_f \left\{ \left| \operatorname{Re} \left\{ \sum_{k=0}^{M-1} (v(2k)^2 - v(2k+1)^2) e^{-j(4\pi f k + 2\hat{\theta} - 2\pi N f)} \right\} \right| \right\}, \quad (9)$$

[0041] Referring to FIG. 8, FIG. 8 shows the root mean square of the modified algorithm 804 in comparison with the basic algorithm 802 and the theoretical Cramer Rao Bound 806. It is seen that the improvement in terms of root-means-square error is very modest between plots 802 and 804. However, graph doesn't account for

cumulative probability distribution error. FIGs. 9-11 account for a cumulative probability distribution error at different signal to noise ratios. From these graphs, it can be seen that the asymptotes are improved by about one order of magnitude. For coded systems, it often means that the performance of the coded system can be improved by an order of magnitude when the system performance is dominated by synchronization error.

[0042] Those skilled in the art can appreciate from the foregoing description that the broad teachings of the present invention can be implemented in a variety of forms. Therefore, while this invention has been described in connection with particular examples thereof, the true scope of the invention should not be so limited since other modifications will become apparent to the skilled practitioner upon a study of the drawings, specification and the following claims.